

ADAPTIVE SEMI-AUTONOMOUS TELEOPERATION OF A MULTI-AGENT ROBOTIC SYSTEM

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ABSTRACT

The primary objective of this paper is to develop an adaptive bilateral impedance control method for a team of mobile robotic agents, which implements formation control, cooperative grasping force compensation, and operator induced error compensation for unconstrained, constrained, and transition motions. In this approach, a leader robot is selected and teleoperated by an operator and the follower robots are autonomously coordinated to make a formation to perform a task of cooperatively transferring an object. By estimating the target dynamics, the bilateral impedances of the system are adjusted to assist the operator in determining grasping forces to have a secure grip of the object. In addition, the formation can be re-configured to avoid collisions with stationary obstacles and among the member robots. The performance of the developed method was investigated through haptic simulations. In the simulation study, a haptic device was used as the master robot, and three virtual omnidirectional mobile platforms were employed to transfer an object. The simulation results demonstrate stable grasping motions of the team of the mobile robot and position and force errors minimized by adapting the bilateral impedances of the system.

1 INTRODUCTION

Over the past decades, several noticeable results have been reported more in Single-Master-Single-Slave (SMSS) than multiple slave robot teleoperation to handle some simple tasks. Similarly, the SMSS and the multiple slave robot teleoperation also prevent a human operator from directly getting into hazardous or inaccessible environment. However, some applications, such as the plant maintenance, construction, and surgery, require many slave robots to simultaneously work in a remote area. In addition, only the multiple slave robotic teleoperation can amplify human effort. Therefore, the Single-Master Multi-Slave (SMMS) teleoperation is studied in this paper.

In the SMMS, because the number of the slave degrees of freedom is more than that of the master degrees of freedom, it is not feasible the system is manually controlled. Nevertheless, a fully automatic control is not also possible when many complex tasks require human flexible intelligence. Therefore, a combination of human and machine controls is necessary. Generally, most of the SMMS applications require robots to handle a bulky object cooperatively. The tasks, such as manipulating a large object with a team of robots and etc, demand all accurate and closely coordinated actions of team members. In [3, 4], Lee and Spong *et al* developed a cooperative multiple slave robot teleoperator to transport an object by autonomously controlling a decoupled grasping shape. Nonetheless, an obstacle avoidance task, a well known issue, in the object transportation heavily relies on human performance in the reported work. The performance is limited by the operators motor skills and his ability to maintain situational awareness [10]. As a result of the bad performance, a human error, i.e. a human command that causes robots and/or environments to be damaged, is easily made. Besides, the grasping stability of the transported object, i.e. pressure exerted by each robot on the object is stable enough to hold it firmly, is necessary [2, 6]. In the SMMS, the different pressures acting on different transported object materials are required to be online determined by an operator or robot. However, in most of the research, [1, 2, 6, 10, 9], their proposed systems do not allow the operator or robot to adjust the pressures based on their own judgments on the object material.

Therefore, the primary objective of this paper is to develop an adaptive bilateral impedance control method that combines formation control, grasping force compensation, and human error recovery. During the operation, the operator only focuses on controlling the leader robot and the follower robots autonomously cooperate to make a formation with the leader based on environmental information. The

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adaptive formation and recovery functions are used to adapt the formation and correct erroneous or drastic operator commands to modify the path for the leader robot. By estimating the dynamics of a target [1, 2], the teleoperator impedances are adapted to assist the operator in determining a grasping force, i.e. the force required to secure a grasp of the object. The force compensators modify their compliances to damp out oscillatory contact with the object [5, 9].

Typical SMMS teleoperation systems are reviewed and an adaptive bilateral control method is developed, which can relieve an operators burden of teleoperating a team of robots in complex environment for an extended period of time. The performance of the proposed system in terms of stability and transparency is verified through haptic simulations.

2 SMMS TELEOPERATION

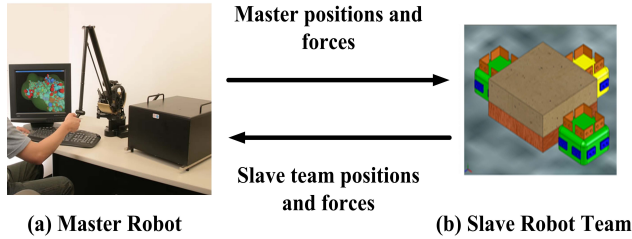


Figure 1: SMMS teleoperation system

Figure 1 (a) and (b) show the master and slave robots of a typical bilateral teleoperator. In general, the linearized dynamic equations of the system are expressed as
Master:

$$M_m(\ddot{x}_m - \ddot{x}_{st}) + B_m(\dot{x}_m - \dot{x}_{st}) + K_m(x_m - x_{st}) = C_2 \frac{1}{\beta} f_{et} - f_h \quad (1)$$

Slave Robotic Team:

$$M_s(\ddot{x}_{st} - \ddot{x}_m) + B_s(\dot{x}_{st} - \dot{x}_m) + K_s(x_{st} - x_m) = C_3 f_h - \frac{1}{\beta} f_{et} \quad (2)$$

$$\frac{\sum_{i=0}^n x_{sFi} + x_{sL}}{n+1} = x_{st} \quad (3)$$

$$\frac{\sum_{i=0}^n f_{eFi} + f_{eL}}{n+1} = f_{et} \quad (4)$$

where for $i=1, \dots, n$, x_{sFi} and x_{sL} are the i^{th} slave followers and leaders positions, respectively. x_m and x_{st} are the $n \times 1$ generalized coordinate vectors representing positions and orientations of the master robot and the slave team or the transported object in their working coordinate systems, respectively. $\dot{x}_m, \dot{x}_{st}, \dot{x}_m$, and \dot{x}_{st} are derivatives of x_m, x_{st}, x_m , and x_{st} , respectively. f_{eFi} and f_{eL} are the $n \times 1$ vectors representing the i^{th} slave followers and leaders sensed force, respectively. f_{et} is the $n \times 1$ vector representing an averaging sum of environmental force sensed by remote sensors on the slave robots, M_m and M_s are the $n \times n$ inertia matrices of the master and each slave, respectively. B_m and B_s are the $n \times n$ vectors of the viscous coefficients of the master and slave team robots, respectively. $\beta \neq 0$ is the force amplification between the robots. f_h is the $n \times 1$ vector of the operational forces applied to the human operator by the master manipulator. K_m, K_s, C_2 , and C_3 are the controller parameters for the bilateral teleoperator. The formation center is computed by using Eqs. (3) and (4) as the location of the team of robots. The transported object is assumed to be constrained to the center of the formation when it is being carried.

The transparency of the system can be measured [3, 4] by such a way that $f_h = f_{et}$ and $x_m = x_{st}$ are achieved. It is noted that the perfect transparency is not realistic because of significant time delays such as control latency, system processing time, communication delay, etc. A variety of robot

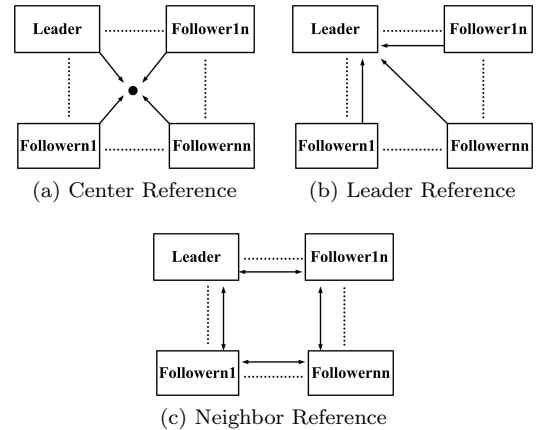


Figure 2: Formations

formations is pursued due to the consideration of different tasks, environments, and/or sensor constraints. Balch and Arkin *et. al.* proposed three different techniques for determining a formation[1], such as the center referenced, neighbor-reference, and leader-referenced formations as shown in Figure 2. The leader-referenced formation is most suitable

for SMMS because the other methods require more computational resources [1].

3 ADAPTIVE BILATERAL CONTROL

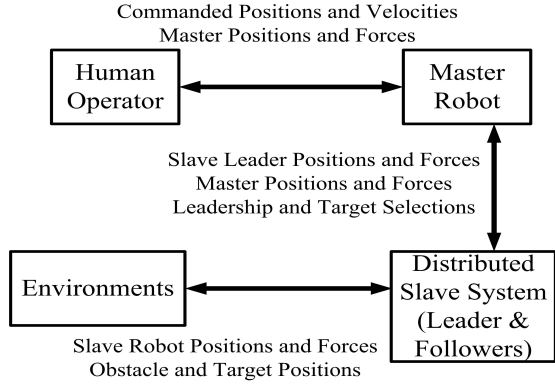


Figure 3: Bilateral SMMS teleoperator

The overall architecture of the proposed system is schematically described in Figure 3. The master and slave systems are connected over wired or wireless internet.

Each subsystem of the bilateral SMMS teleoperation system is presented in Figure 4. The equations of motion of the systems can be rewritten as Master:

$$M_m \ddot{e}_m + \hat{B}_m \dot{e}_m + K_m e_m = f_h - f_{eL} \quad (5)$$

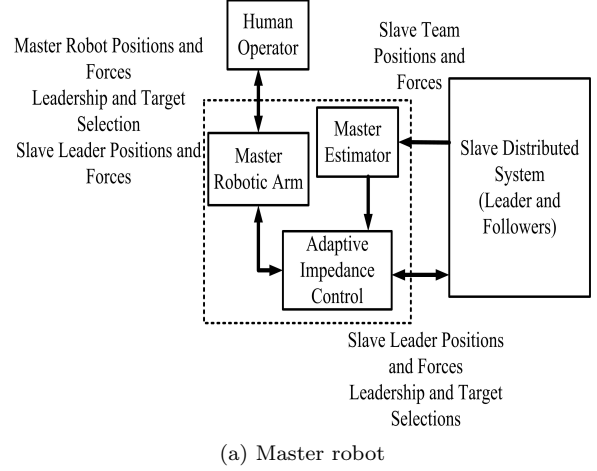
Slave Leader:

$$M_{sL} \ddot{e}_{sL} + M_{sL} \beta_1 \dot{e}_{sL} + M_{sL} \beta_0 e_{sL} = v_{sL}^T \tilde{a}_{sL} + (1 - W)(C_e \delta F_{eL} + U_o) \quad (6)$$

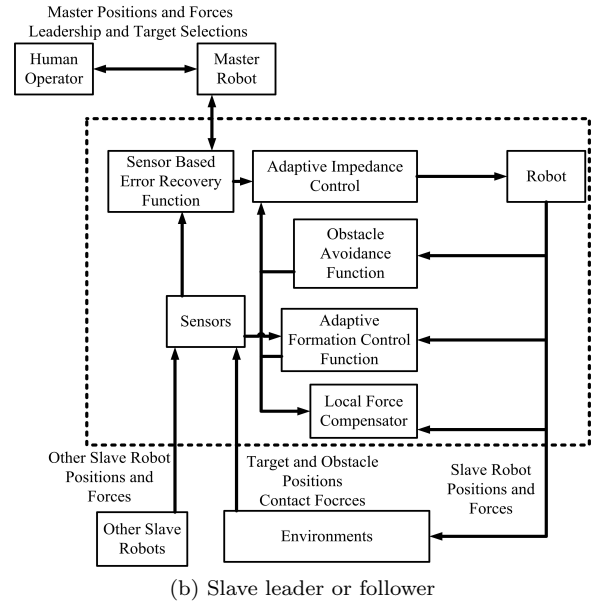
Slave Follower:

$$M_{sFi} \ddot{e}_{sFi} + M_{sFi} \beta_1 \dot{e}_{sFi} + M_{sFi} \beta_0 e_{sFi} = v_{sFi}^T \tilde{a}_{sFi} + U_f + (1 - W)(C_e \delta F_{eFi} + U_o) \quad (7)$$

where M_m , K_m , and f_h are defined previously. For $i = 1, \dots, n$, M_{sL} and M_{sFi} are the $n \times n$ inertia matrices of the leader and i^{th} follower, respectively. \ddot{e}_m , \ddot{e}_{sL} , \ddot{e}_{sFi} , \dot{e}_m , \dot{e}_{sL} , and \dot{e}_{sFi} are the derivatives of \dot{e}_m , \dot{e}_{sL} , \dot{e}_{sFi} , e_m , e_{sL} , and e_{sFi} , respectively. $e_m = x_m - x'_{sL}$, $e_{sL} = x_{sL} - x'_m$, and $e_{sFi} = x_{sFi} - x_{sFdi}$. x_{sFi} is the measured i^{th} slave follower's position. x_{sFdi} is the desired position of the i^{th} follower with respect to the leader's position. x_m is the position of the leader. x'_m and x'_{sL} are the delayed transmitted masters and leaders positions, respectively. β_1 and β_0 are the positive constants chosen such that $s^2 + \beta_1 s + \beta_0$ is a stable (Hurwitz) polynomial. \hat{B}_m is the master adaptive impedance gain which is regulated based on



(a) Master robot



(b) Slave leader or follower

Figure 4: Architecture of the developed SMMS system

an estimate of the environment. $v_{sL} = [z_{sL} \dot{x}_{sL} x_{sL}]^T$. \dot{x}_{sL} is the derivative of x_{sL} . $z_{sL} = \ddot{x}'_m - \beta_1 \dot{e}_{sL} - \beta_0 e_{sL}$ where \ddot{x}'_m is the delayed transmitted acceleration. $\tilde{a}_{sL} = [W \hat{M}_{sL} - M_{sL} W \hat{B}_{sL} - B_{sL} W \hat{K}_{sL} - K_{sL}]^T$. \hat{M}_{sL} , \hat{B}_{sL} , and \hat{K}_{sL} are the adaptive control gains for the leader. B_{sL} and K_{sL} are the $n \times 1$ vectors that represent the viscosity of the dynamics of the leader and controller parameters, respectively. $\delta F_{eL} = f_{edh} - f_{eL}$. f_{eL} is the forcing function for the leader. f_{edh} is the operators input force and W is the switching gain. C_e is the force compensator gain and U_o is the obstacle avoidance gain. $v_{sFi} = [z_{sFi} \dot{x}_{sFi} x_{sFi}]^T$. \dot{x}_{sFi} is the derivative of x_{sFi} . $z_{sFi} = \ddot{x}'_{sFdi} - \beta_1 \dot{e}_{sFi} - \beta_0 e_{sFi}$. \ddot{x}'_{sFdi} is the delayed transmitted acceleration. $\tilde{a}_{sFi} = [W \hat{M}_{sFi} - M_{sFi} W \hat{B}_{sFi} - B_{sFi} W \hat{K}_{sFi} - K_{sFi}]^T$. \hat{M}_{sFi} , \hat{B}_{sFi} , and \hat{K}_{sFi} are the i^{th} followers adaptive control gains. B_{sFi} and K_{sFi} are the $n \times 1$

vectors that represent the damping coefficients of the dynamics of and control parameters for the i^{th} follower, respectively. $\delta F_{eFi} = f_{edi} - f_{eFi}$. f_{eFi} and f_{edi} are the actual and desired contact force on each follower, respectively. U_f is the formation control gain.

In Figure 4, the obstacle avoidance U_o and adaptive formation control U_f functions in Eqs.(5)-(7), are written as respectively

$$U_o = \begin{cases} \phi \langle -k_e \delta D_1 - b_e \delta V_1 \rangle & \text{if } \delta x_o < r_{imin}, \\ 0 & \text{if } \delta x_o \geq r_{imin}. \end{cases} \quad (8)$$

$$U_f = -k_f(r_{smin} - \delta x_{sFi}) \quad (9)$$

where $\delta V_1 = 1 - \frac{\delta x_o}{r_{imin}}$, $\delta D_1 = r_{imin} - \delta x_o$, r_{imin} and r_{smin} are the minimum distances that a robot needs to keep away from obstacles, e.g. the other robots and actual obstacles. x is the position vector of each slave robot or follower robot. δx_o is the distance between the robot and obstacles. δx_{sFi} is the distance between a robot and the leader. ϕ is the auto-selected parameters. k_e , k_f , and b_e are the two stiffness and damping coefficients, respectively. Eqs.(8) and (9) enable a robot to automatically prevent collisions with obstacles and other team robots. The values of U_o and U_f are computed to regulate slave robot paths based on sensed various robot-leader and robot-obstacle distances. Since the robot team keeps moving in a formation, the equations enable a robot to maintain a distance from the leader. However, its position relative to the leader can change. Therefore, the formation is changed, ensuring that all followers closely track the leader.

The local force compensator and sensor based auto-switching function are written respectively as

$$C_e = \gamma[1 - \exp(-\alpha|\delta F_e|)] \quad (10)$$

$$W = \gamma_w \exp(-\rho|\delta F_e| - \varphi|r_{imax} - \delta x_{sFi}|) \quad (11)$$

where δF_e is the difference of the actual and desired contact forces for the leader and a follower or two followers. α , φ , ρ , and γ are the positive constants. γ_w is the positive sensitivity constant, $1 \geq \gamma_w \geq 0$. A Bezier approximation, Eqs.(10)&(11) are used to provide a smooth transition between manual and autonomous control inputs.

The good transparency is only maintained when the forces do not differ from the reference forces prescribed by the operator. The local force compensator is used to accommodate the excessive force by changing their paths. The described local intelligences in the system are used to keep a condi-

tional transparency and stable grasp of the object if the object is transported.

4 HAPTIC SIMULATIONS

Table 1: Descriptions of the different control methods in the SMMS simulations

Sim	Control Method	Dynamic Equation	Formation Method
1	Impedance Control	Eqs.(1)-(4)	Fixed
2	Adaptive Impedance	Eqs.(5)-(11)	Adaptive

Two haptic simulations, Sim 1 and Sim 2 with two different control methods as described in Table 1 were performed to quantify system performance in the presence of a constant communication delay, all of which involved a human operator in a control loop.

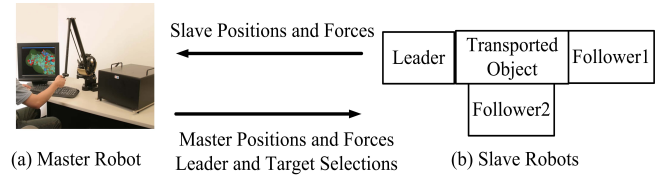


Figure 5: Haptic simulation of a SMMS semi-autonomous teleoperation system

As shown in Figure 5 (a) and (b), Phantom, a 6-DOF haptic device was used as the master system and virtual robots as the team of slave robots. The team as shown in Figures 1 (b) and 5 (b) has a workspace approximately 100 times the master robots. This configuration is representative of an actual teleoperation system used for industrial applications [9].

The virtual team consists of three omnidirectional mobile robots programmed in Visual C++ and OpenGL [5, 9, 11] without a gripper. Therefore, the three robots can only push an object against each other to transport it from one place to another. Impedance control has been the main approach to many applications of teleoperation such as material transportation and obstacle avoidance [8, 12]. In order to simplify and highlight the problems, a well-defined task was used in the simulation study, the objectives of which include obstacle avoidance, human command error recovery, and robust transportation of an object

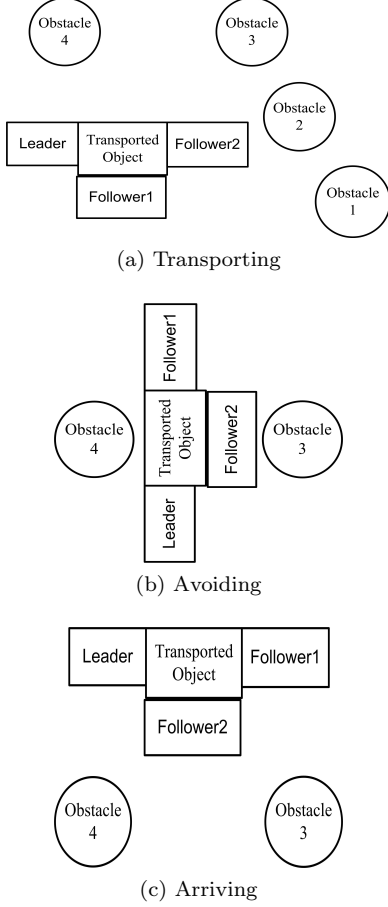


Figure 6: Simulated tasks

subject to a constant communication delay of 0.1 seconds. The communication delay was chosen in the simulations because there is a critical value, beyond which the system will tend to become unstable [7]. The desired distance between two robots was set to 5m. The minimum distance between a robot and an obstacle was set to 5m. Six static circular objects with the radii of 15m were used in each simulation.

The objectives of the task of transporting an object is to make stable contacts with the object and avoid any obstacles. The omnidirectional movable slave robots with three wheels tightly touching the ground were simulated. Only two directions parallel to the ground were considered in the simulations. The master and slave forces and positions were measured through the haptic device and divided by 10, respectively. The team robots with carrying the object were moved from the origin to the final destination by passing through the area full of obstacles in Figure 6. In the simulations, the following parameters were used:

$$M_m = 3 \text{ kg}, K_m = 6 \text{ Ns/m}, M_{sL} = 30 \text{ kg}, B_{sL}$$

$$= 1.0 \text{ Ns/m}, K_{sL} = 60 \text{ N/m}, M_{sFi} = 30 \text{ kg}, B_{sFi} = 1.0 \text{ Ns/m}, K_{sFi} = 60 \text{ N/m}, k_e = 100, b_e = 60, r_{imin} = 5, r_{smin} = 5, k_f = 1, \alpha = \rho = 1, \beta_1 = 10000, \beta_0 = 500, \text{ and } \varphi = \gamma = \gamma_w = 1$$

In the simulation, no friction, gravity, and air resistance were assumed in the environment. If the contact forces in any direction exceeds 0.7 N, the object and robots were assumed to be damaged. The slip was programmed to occur between the robot and the object only if the static friction condition [18] was not met, i.e. the pushing force larger than the maximum allowable static friction force where the friction coefficient was assumed to be 0.5. In the simulation, the slave forces are f_{et} . The position errors are e_m , e_{sL} , and e_{sFi} . The force errors are δF_{eFi} and δF_{eL} .

4.1 Obstacle Avoidance and Contact Stability

Sim 2 was run with adaptive formation and force compensation as opposed to Sim 1. As depicted in Figures 17-20, the force compensator kept stable contacts with the transported object while the tracking performance was compromised for obstacle avoidance. The followers autonomously rotated the object about the axis normal to the ground as shown in Figures 14-20 to avoid the obstacles while satisfying the following three conditions: (1) The distance between any two robots was unchanged. (2) The distances between robots and obstacles were always larger than the required safety distance. (3) The object was grasped firmly. Nonetheless, as shown in Figures 7-13, the operator was able to pass through the area full of obstacles without collision.

4.2 Human Command Error Recovery and Transparency

In Sim 2, it is noted that the human operator did not necessarily give accurate commands to the team to avoid the obstacles. Each robot has its own capability to choose whether to compromise or enhance tracking performance between the master and itself. As seen in Figures 17-20, the tracking performance was sacrificed due to human errors during the time period of 225 -280 seconds but improved before 225 seconds and after 280 seconds. Except the stated time period, the position errors as shown in Figures 17 and 18 were smaller than those in Figures 10 and 11.

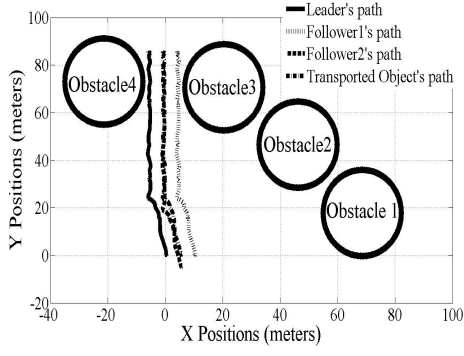


Figure 7: **Sim 1** - Actual paths

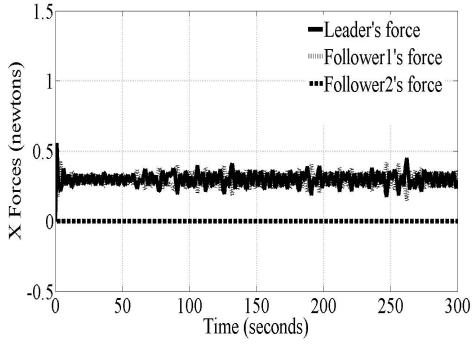


Figure 8: **Sim 1** - Grasping forces in the x-Direction

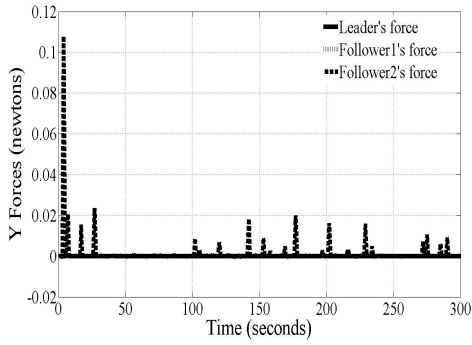


Figure 9: **Sim 1** - Grasping forces in the y-direction

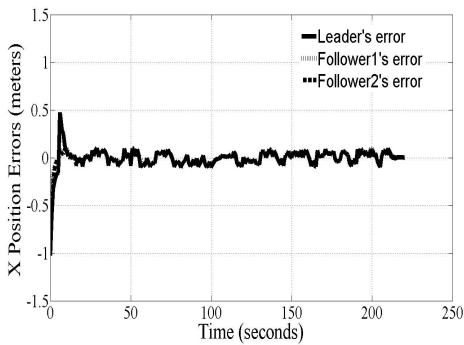


Figure 10: **Sim 1** - Position errors in the x-direction

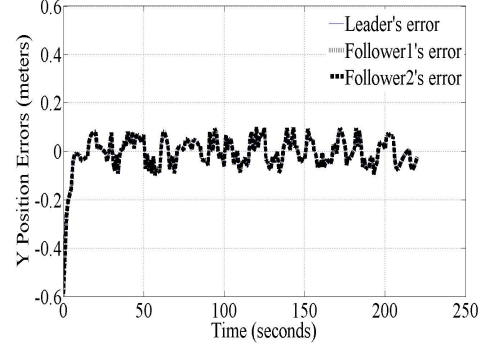


Figure 11: **Sim 1** - Position errors in the y-direction

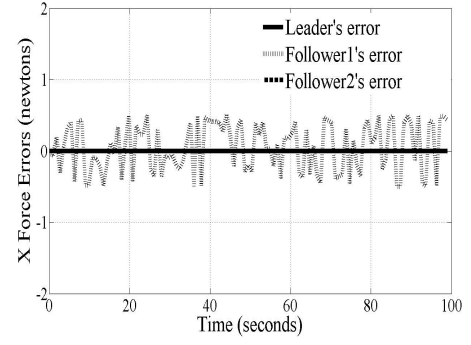


Figure 12: **Sim 1** - Force errors in the x-direction

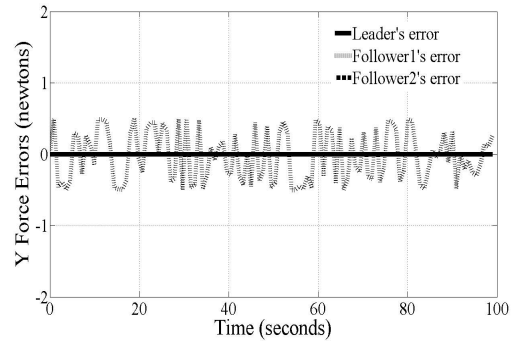


Figure 13: **Sim 1** - Force errors in the y-direction

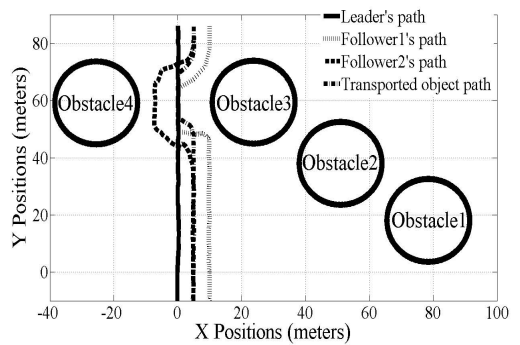


Figure 14: **Sim 2** - Actual paths

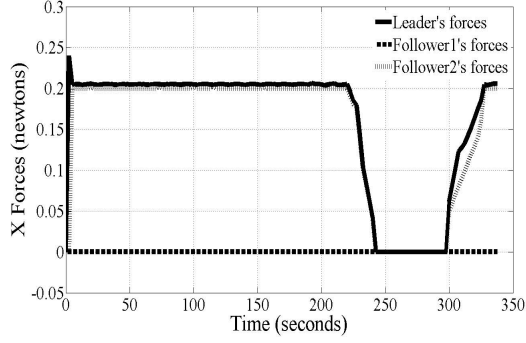


Figure 15: **Sim 2** - Grasping forces in the x-direction

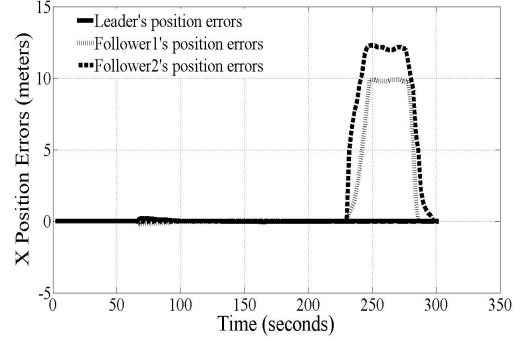


Figure 17: **Sim 2** - Position errors in the x-direction

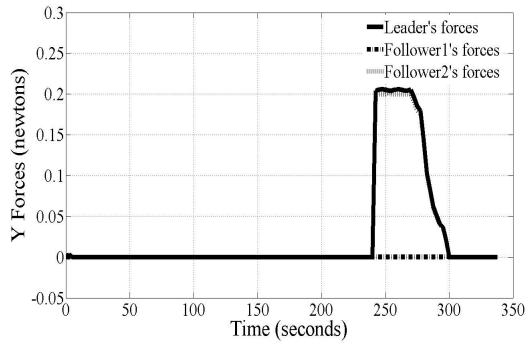


Figure 16: **Sim 2** - Grasping forces in the y-direction

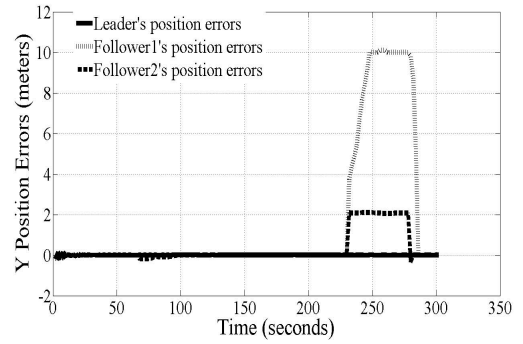


Figure 18: **Sim 2** - Position errors in the y-direction

CONCLUSIONS

The primary objective of this paper was to develop an adaptive bilateral impedance control method for a team of mobile robotic agents, which implements formation control, cooperative grasping force compensation, and operator induced error compensation for unconstrained, constrained, and transition motions. In this approach, a leader robot is selected and tele-operated by an operator and the follower robots are autonomously coordinated to make a formation to perform a task of cooperatively transferring an object. By estimating the target dynamics, the bilateral impedances of the system are adjusted to assist the operator in determining grasping forces to have a secure grip of the object. In addition, the formation can be re-configured to avoid collisions with stationary obstacles and among the member robots. The performance of the developed method was investigated through haptic simulations. In the simulation study, a haptic device was used as the master robot, and three virtual omnidirectional mobile platforms were employed to transfer an object. The simulation results demonstrate stable grasping motions of the team of the mobile robots and position and force errors minimized by adapting the bilateral impedances of the system. The human com-

mand error recovery and force compensation does not modify the existing designs of industrial robots, such as mounting a passive compliant device on the tip. The performance in terms of transportation efficiency and grasp stability, of the developed method was validated through haptic simulations subject to a constant delay. With the developed method, stable grasping was obtained through modification of the commanded trajectory, and the position and force errors were minimized by adapting the master-slave impedance.

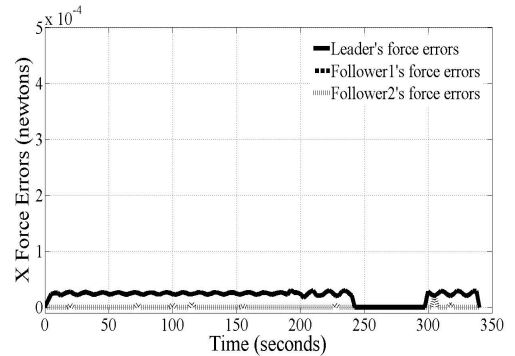


Figure 19: **Sim 2** - Force errors in the x-direction

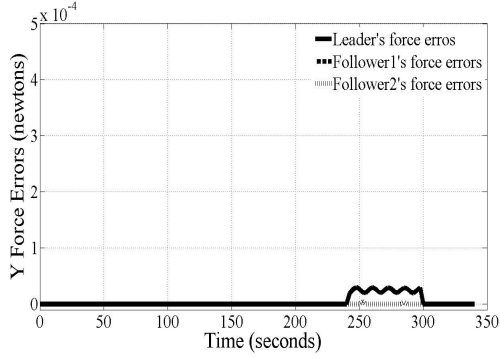


Figure 20: **Sim 2** - Force errors in the y-direction

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